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Neutron and Gamma-Ray Dose Measurements at Various Distances from the Little Boy Replica

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NEUTRON AND GAMMA-RAY DOSE MEASUREMENTS AT VARIOUS DISTANCES FROM THE LITTLE BOY REPLICA*

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Abstract

We measured neutron and gamma-ray dose rates at various distances from the Little Boy-Comet Critical Assembly at Los Alamos National Laboratory (LANL) in April of 1983. The Little Boy-Comet Assembly is a replica of the atomic weapon detonated over Hiroshima, designed to be operated at various steady-state power levels. The selected distances for measurement ranged from 107 m to 567 m. Gamma-ray measurements were made with a Reuter-Stokes environmental ionization chamber which has a sensitivity of 1.0 μR/hour. Neutron measurements were made with a pulsed-source remmeter which has a sensitivity of 0.1 μrem/hour, designed and built at Lawrence Livermore National Laboratory (LLNL).

Introduction

Since the mid-sixties, the dose to each Japanese nuclear weapon survivor has been calculated using the ICHIBAN or T65D (tentative 1965 dose) estimates.[1] These dose estimates were based primarily on data obtained from atmospheric nuclear weapon tests, Operation BREN, laboratory experiments, and physical surveys in Japan.

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Recently, several groups have used state-of-the-art radiation-transport computer codes and revised source-term estimates to recalculate the doses the survivors received.[2,3] In most cases, these doses differ from the ICHIBAN estimates, particularly the neutron dose component at Hiroshima. LANL constructed the Little Boy replica so that bench-mark-quality measurements could be made to validate the computer calculations. The Little Boy spectrum is much softer than bare-metal U-235 critical assemblies (such as the Health Physics Research Reactor) due to the large quantities of tungsten steel in the weapon casing. Experimenters have used the replica to evaluate weapon yield, leakage spectra as a function of angle, in-situ dosimeters (such as roof tiles and electrical transmission on line insulators), and dose rates as a function of distance from the replica.[4] We made neutron-dose-equivalent rate and gamma-exposure rate measurements at distances of 107 m to 567 m from the Little Boy replica.

Description of the Environment

The Little Boy replica is almost an exact duplicate of the gun-type device detonated over Hiroshima. The non-nuclear components were obtained from a similar device which had been retired from the stockpile. Adequate fissile U-235 was placed in the replica to allow steady-state (sustained delayed critical) operation of the replica.

The Little Boy replica was mounted on the Comet Assembly Machine at the Los Alamos Critical Assembly Facility located in Pajarito Canyon, New Mexico. To eliminate room-scatter complications in our measurement, the Comet Assembly Machine was moved out of the assembly building so that it would be away from all structures. It was mounted in a nose-up position, with the center of the assembly core at four meters above the canyon floor. The four-meter core height reduced ground scatter at measurement points near the assembly. Operation of the assembly without control rods was achieved by precision screw and hydraulic lift mechanisms.

An aerial view of the experimental area is shown schematically in Fig. 1. The Comet Assembly Machine was located at Kiva II in Three Mile Canyon, approximately 390 meters from the control room. The distances between the replica and the seven measurement points are shown in Table 1.

Table 1. Measurement Point Distances

Measurement point	Location	Distance (meters)
1	Along access road	107
2	Along access road	198
3	At access gate	293
4	Near control room	363
5	Near guard station	408
6	Road junction	560
7	Edge of mesa top	567

Note the difference between measurement points 6 and 7. Although they are at approximately the same range, point 6 is on the valley floor while point 7 is on the edge of the mesa top.

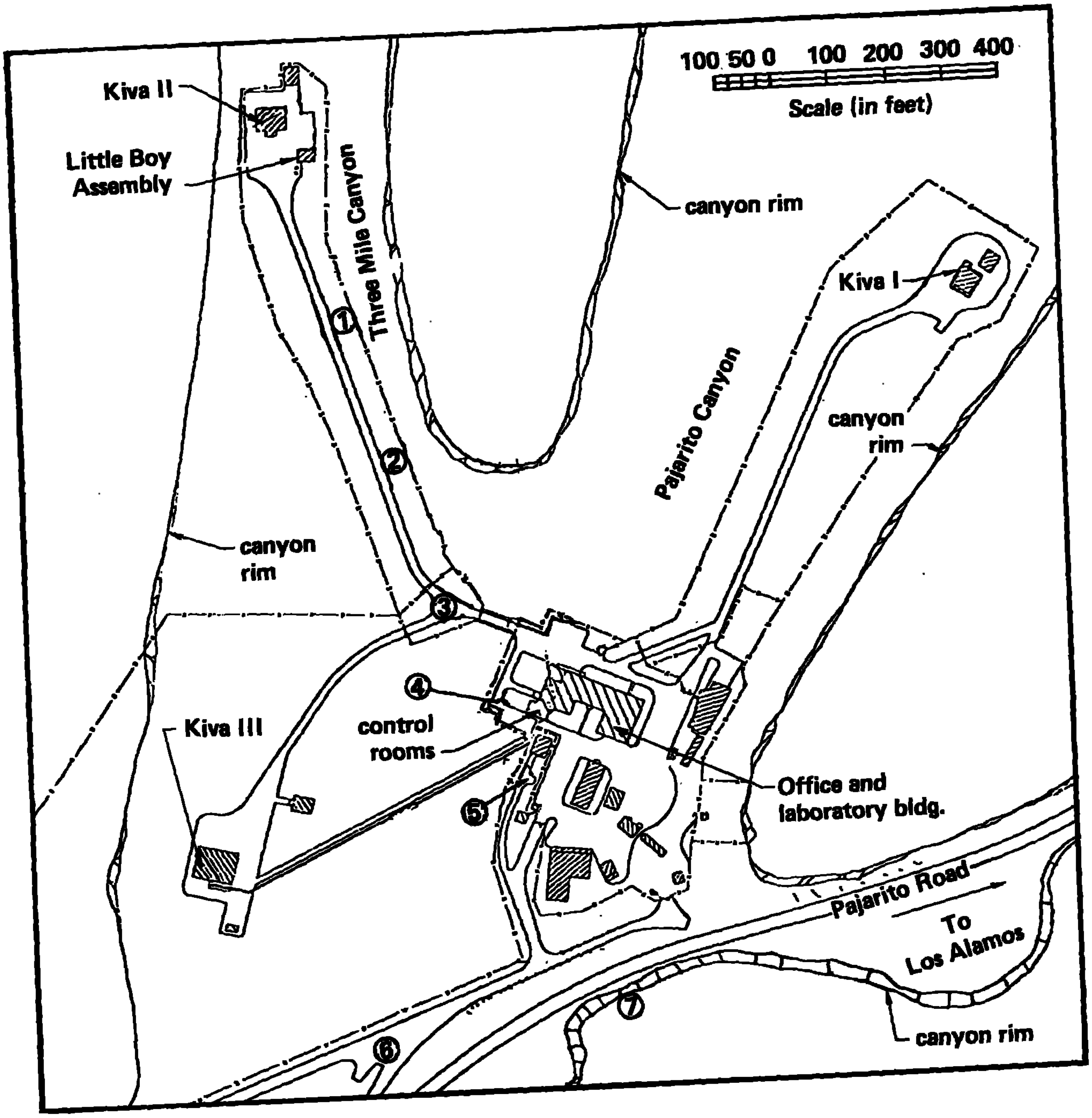

Figure 1 -- Experimental area.

Atmospheric Data

The measurements at points 6 and 7 (560 meters and 567 meters) were made during the evening of 28 April 1983, between 19:00 and 20:30. The measurements at points 1 through 5 were made the following morning, 29 April 1983, between 9:00 and 11:00. The dry-bulb temperature, relative humidity, and atmospheric pressure were recorded at hourly intervals while we made radiation measurements. The mean atmospheric conditions during the measurement periods are reported in Table 2. The comparatively low atmospheric pressure due to the high elevation had the greatest influence on the air density. For comparison, the mean moist-air density at Hiroshima was 1.14 kg/m^3.[5]

Table 2. Mean Atmospheric Conditions

Meteorological Parameters	Measurement Points	
	1-5	6-7
Dry bulb temperature (°C)	11	14
Relative humidity (%)	22	14
Atmospheric pressure (mm Hg)	591.1	590.3
Wet bulb temperature (°C)	3	5
Dew point (°C)	-9	-11
Moist air density (kg/m^3)	0.965	0.955

Instrumentation

We selected the gamma and neutron instruments for their sensitivity, known energy dependence, and reduced response to unwanted radiations. All measurements were made one meter above the ground. The neutron detector we used was the pulsed-source remmeter developed at LLNL by Thorngate, et al.[6] The instrument was designed to measure pulsed neutrons, but was selected for our measurements because of its high sensitivity (23,900 counts/mrem). The pulsed-source feature was not necessary because the Little Boy replica was operated at a steady-state power level. Like most remmeters, this unit has a thermal neutron detector mounted in a polyethylene moderator. The detector is a lithium glass scintillator 3.2-mm thick and 25.4-mm in diameter, containing 6.6% lithium enriched to 94% Li-6 (Nuclear Enterprise's Model 905). The crystal is surrounded by a 28.3-cm diameter polyethylene sphere. The energy dependence of the remmeter (Table 3) is similar to that of other remmeters such as the Andersson-Braun or 9-in. sphere, having an over-response to lower energy neutrons. We calibrated the remmeter with a bare Ca-252 source at the LLNL Standards and Calibration Facility.

Table 3. Comparison of Neutron Remmeter Spectral Responses

Source	Average energy (MeV)	Response nrem/(n/cm^2) Andersson Braun	9-in. sphere (PNR-4)	Pulsed-source remmeter
^{252}Cf + 25 cm D_2O	0.092	14.6	17.9	19.9
$^7Li(p,n)\ ^7Be$	0.097	--	--	15.0
$^3H(p,n)\ ^3He$	0.42	--	--	17.5
^{252}Cf + 10 cm D_2O	0.59	23.0	24.4	23.9
Bare ^{252}Cf	1.4	41.3	41.3	39.3
$^3H(p,n)^3He$	1.42		--	32.9
$^3H(p,n)^3He$	2.19	--	--	41.6
Bare $^{238}PuBe$	2.5	36.8	38.8	39.1
$^3H(d,n)\ ^4He$	10.6	22.6	26.5	29.3

Note 1: All remmeter responses are normalized to a unit neutron flux.

Note 2: Cf-252, PuBe, and d,T neutron average energies obtained from ANISN (a one-dimensional, discrete ordinate, radiation transport computer code) calculations for a fixed source-detector configuration in the Hazards Control low-scatter irradiation facility.[7]

The pulsed-source remmeter's response to photons below 1 MeV is effectively suppressed by the internal electronic threshold setting. The response to 100 mR from Cs-137 was only 4 μrem. Higher sensitivities are exhibited for photons between 1.0 and 2.5 MeV. For example, the response was 1.5 mrem for a Co-60 gamma exposure of 24 mR. Response to photons above 2.5 MeV is effectively limited by the size of the detector. At most, only 4% of the counts obtained from an exposure to a PuBe source could be attributed to gamma-ray interactions (4.4 MeV gamma from the source and 2.2 MeV gammas from neutron captures in the polyethylene sphere).

Gamma-ray dose rate measurements were made with an RSS-111 Environmental Radiation monitor manufactured by Reuter-Stokes. The spherical detector has a 25.4-cm diameter and an 8-litre sensitive volume. It is filled with ultra-pure argon gas at a pressure of 2.5 MPa (25 atm). The wall of the detector is 3-mm-thick 304 stainless steel. Figure 2 shows the energy dependence of the instrument. The response is fairly flat from 10 MeV down to approximately 70 keV; below 70 keV the sensitivity falls off rapidly. The unit was calibrated by Reuter-Stokes with Co-60.

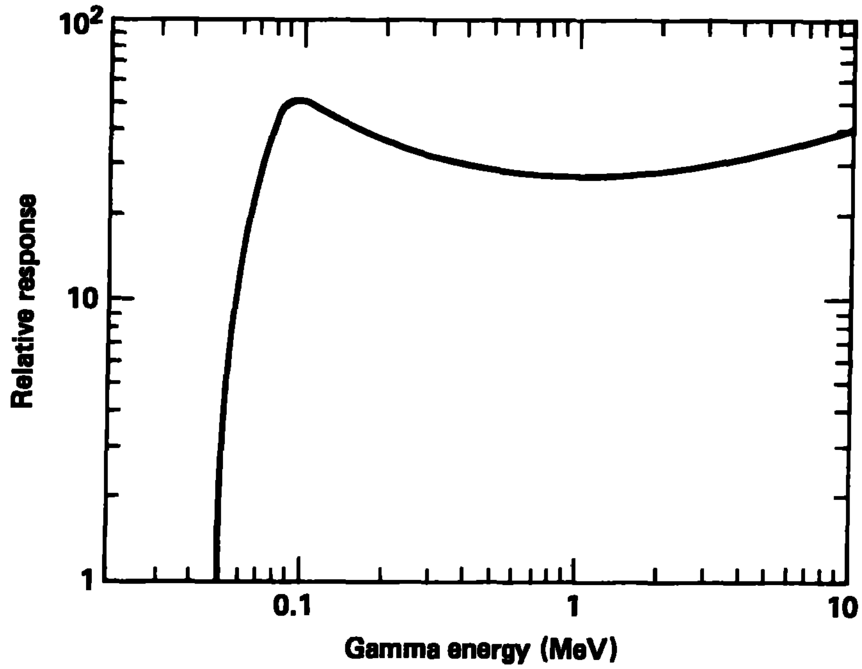

Figure 2 -- Reuter-Stokes energy dependence.

The environmental gamma monitor has practically no hydrogenous material in the detector housing, providing little chance that fast neutrons will be thermalized. When exposed to thermal neutrons, the stable Ar-40 detector gas may be activated to Ar-41 ($T_{1/2}$ = 1.83 h). This reaction has a 0.5 barn cross-section. We made background measurements before and after making the field measurements. We saw no change in the background level after the field measurements which would indicate argon activation. Therefore, we assumed that the neutron contribution to our gamma measurements is negligible.

Experimental Results

Tables 4 and 5 summarize the results of our measurements. The measurement locations coincide with the points shown on the map in Fig. 1. In some cases, measurements at different reactor power levels were made at the same location. The dose equivalent rates and exposure rates have been corrected for background. All of the values are normalized to the core fission rate. The calibration of the fission rate was done by radiochemical analysis of fission foils.[8]

The results are depicted graphically in Figs. 3 and 4. The data points have been fitted by linear regression. Errors (one standard deviation) for the linear-regression fit of our data points are also shown at 100, 300, and 600 meters. The shape and slope of the curves for the neutrons and gamma rays are different, but both show a drop which is clearly much more rapid than the inverse-square relationship predicts. Data by Hoots and Wadsworth are also presented.[9] The atmospheric density during their measurements was calculated to be 0.944 kg/m^3, very similar to the density during our measurements. Our two sets of data agree within the calculated statistical variation of the measurements. The only exception is the neutron dose measurements at

600 meters. This may be explained by statistical counting errors at the low neutron dose rate. Plassman and Pederson made similar measurements;[10] we did not include their data, however, because they did not report the atmospheric conditions at the time of their measurements.

Table 4. Neutron Dose Equivalent Rates at Selected Distances From the Assembly

Measurement Point	Location	Range (meters)	Reactor Power Level (fission/sec)	Net Neutron Dose Equivalent rate (mrem/hr)	Normalized Dose Equivalent (rem/fission)
1	along road	107	5.09E9 1.78E10	0.303 0.958	1.654E-17 1.493E-17
2	along road	198	1.66E11	2.158	3.620E-18
3	at gate	293	1.66E11	0.445	7.464E-19
4	near control room	363	4.55E11	0.530	3.236E-19
5	near guard station	408	4.55E11	0.342	2.088E-19
6	road junction	560	9.20E12 1.66E13 1.64E12	1.338 2.618 0.279	4.040E-20 4.391E-20 4.731E-20
7	mesa top	567	4.55E11	0.064	3.907E-20
background	valley floor and mesa top			0.012	

Table 5. Gamma Exposure Rates at Selected Distances From the Assembly

Measurement Point	Location (meters)	Range (meters)	Reactor Power Level (fission/sec)	Net Gamma Exposure Rate (μR/hr.)	Normalized Exposure (R/fission)
1	along road	107	5.09E9 1.78E10	15.5 38.5	8.461E-19 6.001E-19
2	along road	198	1.66E11	90.5	1.518E-19
3	at gate	293	1.66E11	26.5	4.445E-20
4	near control room	363	4.55E11	35.5	2.167E-20
5	near guard station	408	4.55E11	22.5	1.374E-20
6	road junction	560	9.20E12 1.64E12	110.5 22.5	3.336E-21 3.816E-21
7	mesa top	567	4.55E11	9.0	5.495E-21
background	valley floor mesa top			9.5 11.0	

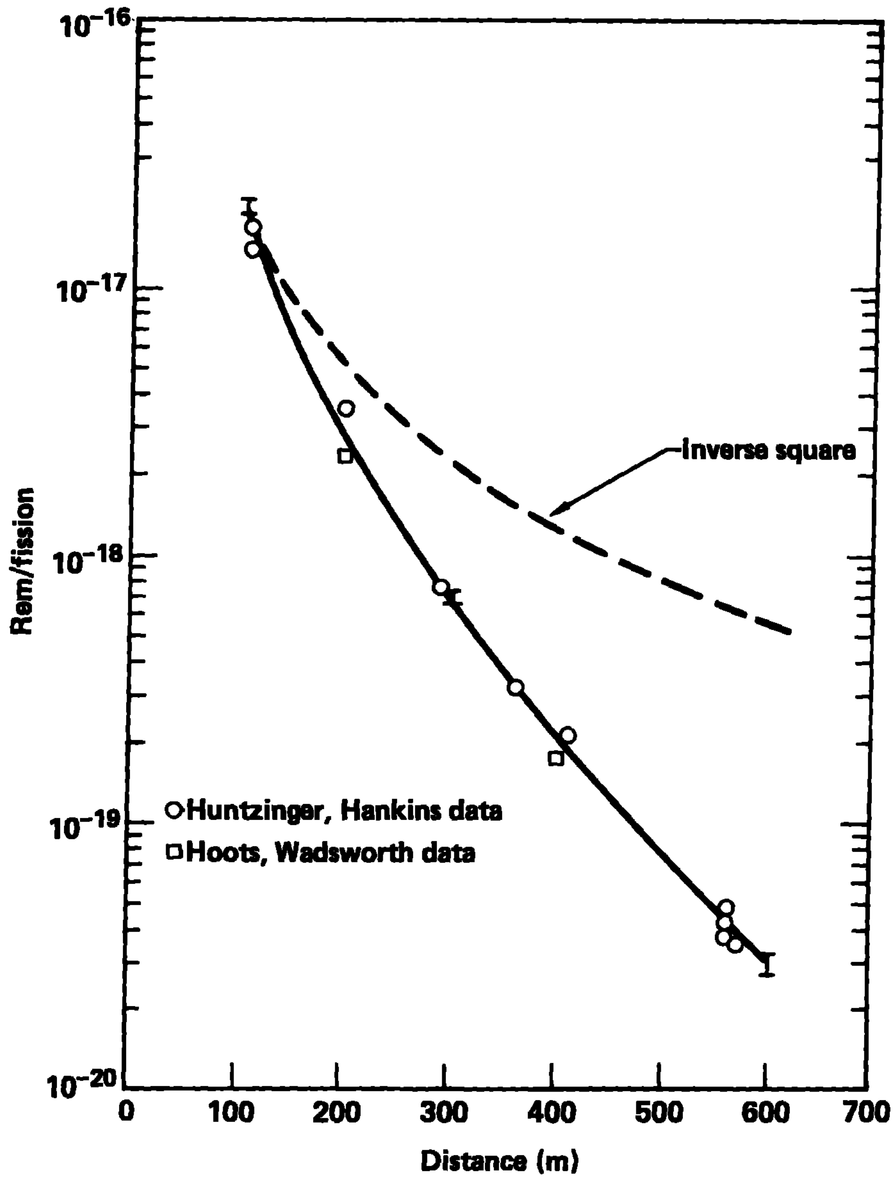

Figure 3 -- Normalized neutron dose per fission vs distance from Little Boy replica.

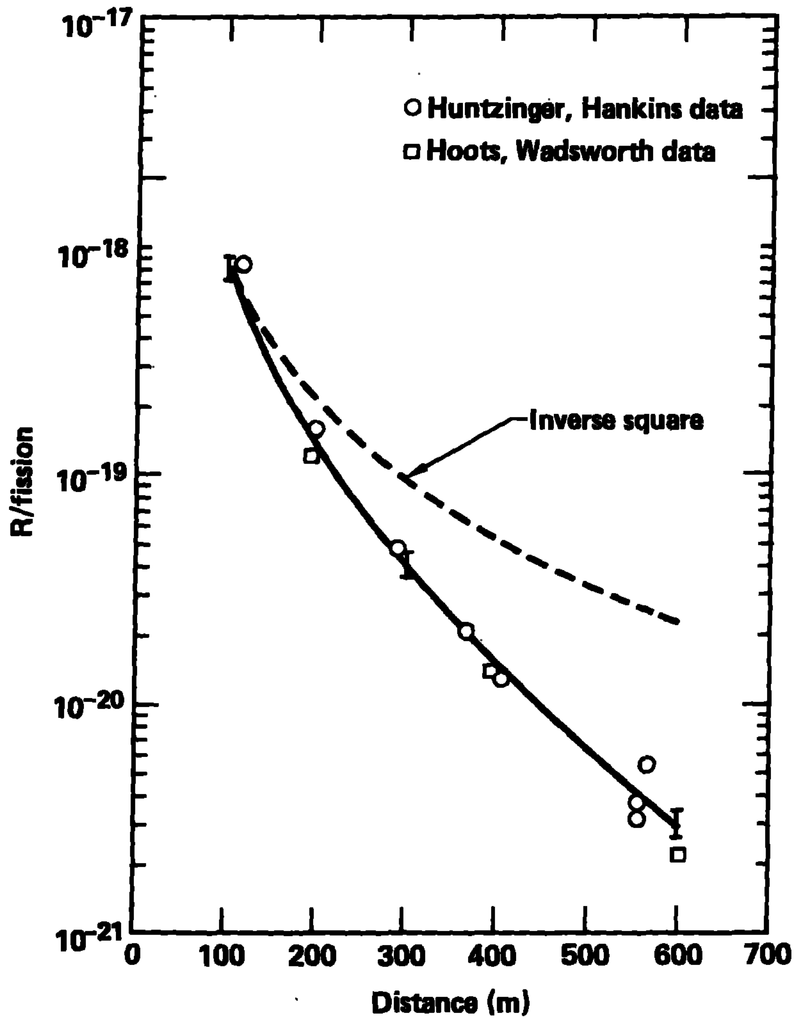

Figure 4 -- Normalized gamma exposure per fission vs distance from Little Boy replica.

In air-over-ground geometries, a quantity called the relaxation length is often used to describe the rate at which radiation doses diminish with distance. In 1959, Ritchie and Hurst developed the following semi-empirical equation which allows calculation of relaxation length:[11]

$$D(r) = \frac{G_o \; e^{-r/L}}{r^2}$$

Where L = relaxation length in meters,

r = range in meters,

G_o = extrapolated source term in (rem)(range)^2 or (R)(range)^2

D(r) = dose or exposure in rem or R.

We calculated the measured relaxation length for neutrons and gamma-rays by fitting our experimental data to this equation. Straker published computer calculations in 1971[12] which showed ground-scatter contributions were significant within 300 meters from a fission source operated 15 meters above the ground surface. Linear regression analysis using our measurement points at 300 meters and beyond yielded a neutron-dose relaxation length of 171 meters and a gamma-ray exposure relaxation length of 256 meters. For comparison, Hoots and Wadsworth[9] calculated neutron and gamma relaxation lengths to be 161 m and 267 m, respectively. These values are in good agreement; however, their values must be considered estimates because they were calculated using only the 198 m and 400 m measurement positions. Plassmann and Pederson[10] calculated neutron and gamma relaxation lengths of 200 and 325 m, respectively. Again, these numbers must be considered estimates because they have only one measurement point at a range greater than 300 m. The ICHIBAN study used 198 m and 250 m for the neutron and gamma relaxation lengths, respectively. While the ICHIBAN relaxation lengths seem to agree with our measurements, it is not appropriate to make a direct comparison between the two studies because of the difference in atmospheric densities and compositions.

Figures 5 and 6 show graphically the data points used to calculate the neutron dose equivalent and the gamma exposure relaxation lengths. Normalized values (rem/fission and R/fission) were used because the replica was operated at the various power levels. Once again, one-standard-deviation errors for the linear-regression fit of our data points are shown.

Another quantity commonly used to characterize a fission source in an air-over-ground geometry is the neutron-to-gamma ratio as a function of distance from the source. We measured dissimilar quantities (rem and R) so we cannot calculate the ratio directly. However, if we assume 1 rad (tissue) = 0.877 R and a quality factor of 1, it is possible to convert the exposure measurements to rem.

The calculated neutron-to-gamma ratios are shown in Table 6 and Figure 7. Values from the linear-regression line through the data points for the relaxation length calculations were used to calculate the neutron-to-gamma ratio. The ratio is a smooth function ranging from 27.5 at 100 meters to 11.2 at 600 meters.

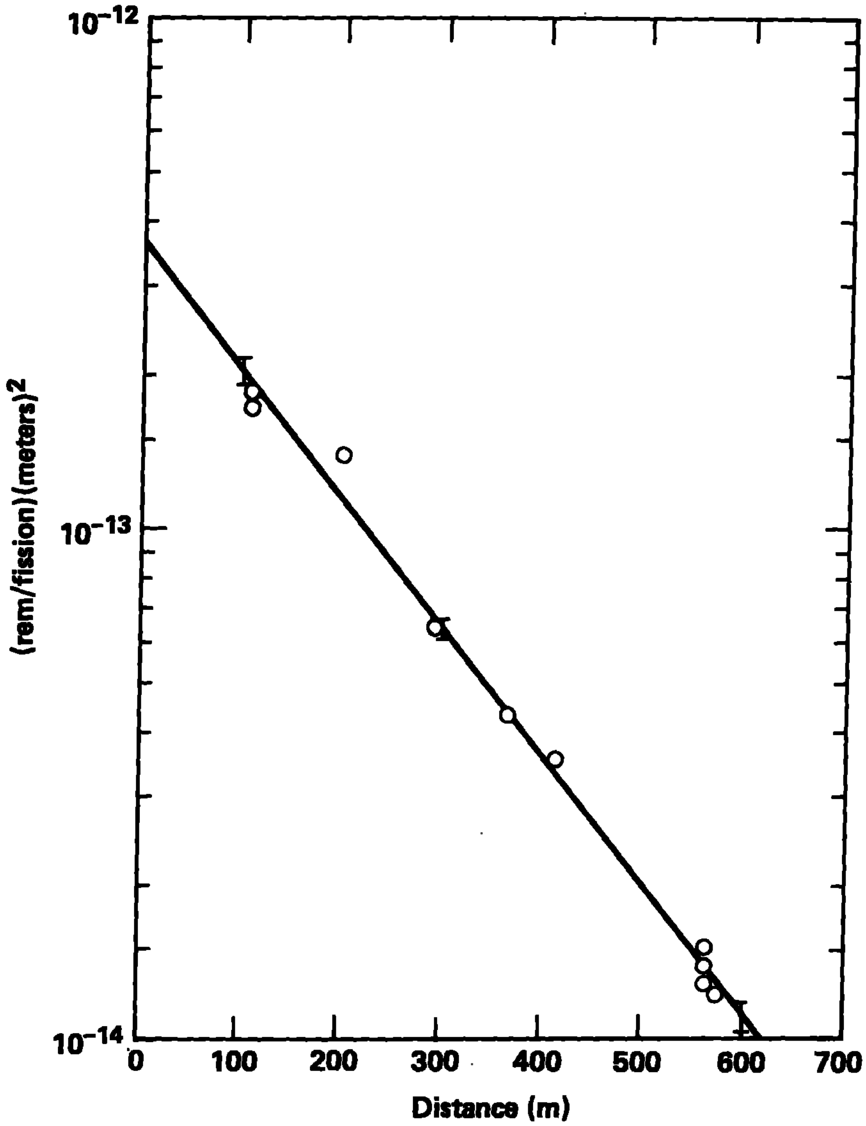

Figure 5 -- Neutron relaxation length for Little Boy replica.

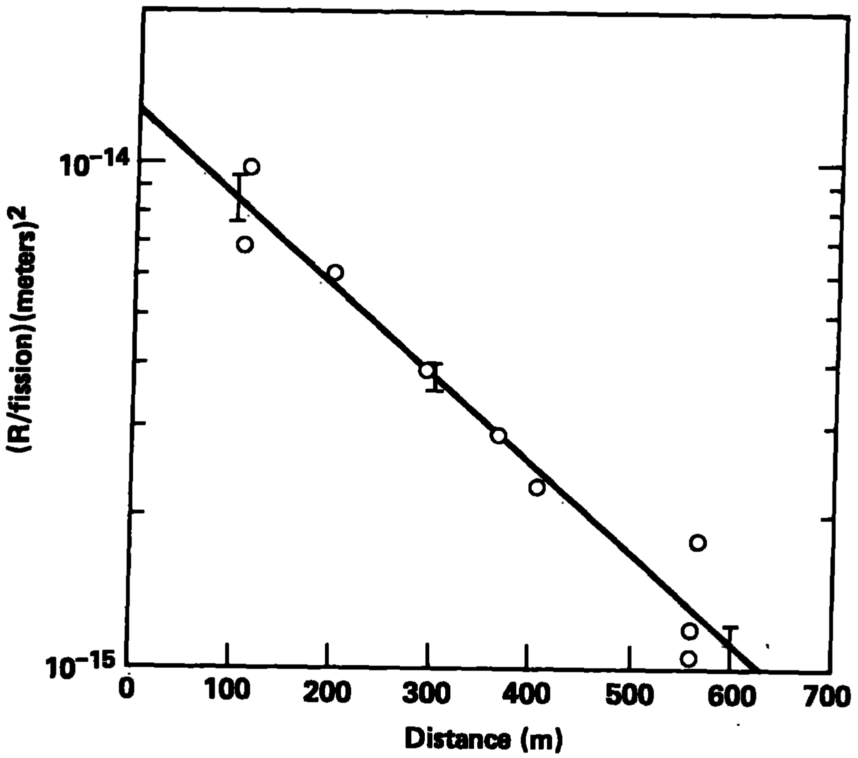

Figure 6 -- Gamma relaxation length.

Table 6. Calculated Neutron-to-Gamma Ratios

Range (meters)	Measured neutron (rem/fission)	Measured gamma (R/fission)	Calculated gamma (rem/fission)	Neutron/gamma ratio
100	2.03E-17	8.42E-19	7.38E-19	27.5
200	2.83E-18	1.40E-19	1.23E-19	23.0
300	7.00E-19	4.16E-20	3.65E-20	19.2
400	2.19E-19	1.56E-20	1.37E-20	16.0
500	7.80E-20	6.64E-21	5.82E-21	13.4
600	3.03E-20	3.08E-21	2.70E-21	11.2

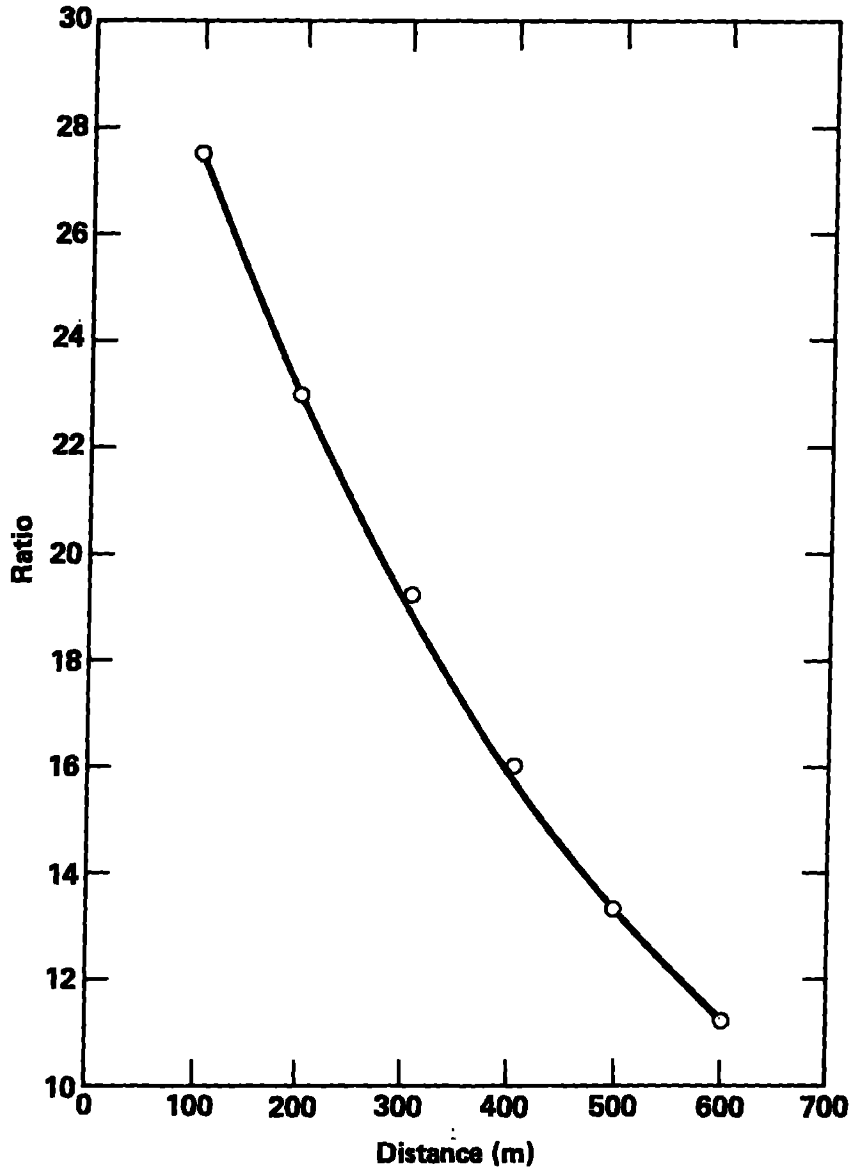

Figure 7 -- Neutron to gamma ratio.

Summary

Our measurements indicate that the neutron-dose-equivalent/fission and gamma-exposure/fission curves decrease with distances at different rates. However, both show a drop which is clearly much more rapid than the inverse-square relationship predicts. We measured a neutron-dose-equivalent relaxation length of 171 meters and a gamma-exposure relaxation length of 256 meters. These values are in agreement with the neutron and gamma relaxation length estimates measured by Hoots and Wadsworth (161 and 267 meters, respectively). The neutron-to-gamma ratio varied smoothly from 27.5 at 100 meters to 11.2 at 600 meters.

Acknowledgments

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